The Chemistry and Morphology of Diagenetic Features in Glen Torridon, Gale Crater

Conference or Workshop Item

THE CHEMISTRY AND MORPHOLOGY OF DIAGENETIC FEATURES IN GLEN TORRIDON, GALE CRATER.

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Introduction: The major, minor, trace chemistry, hydration, and mineralogy of diagenetic features, including fracture fill "veins," cements, and concretions, help shed light on the aqueous processes of ancient Mars [e.g., 1–7]. The chemistry and morphology of these features help constrain the conditions of the subsurface fluids; their cross-cutting relationships can be used to help understand the timing and duration of these diagenetic events. Constraints on timing and conditions add to our understanding of the long-term habitability of martian groundwater. Diagenetic features are ubiquitous in the Murray formation [1–7], and a large diversity of these features are present in "Glen Torridon" (GT): a phyllosilicate-rich fluvio-lacustrine mudstone and sandstone deposit in Gale crater.

The NASA *Curiosity* rover is approaching the "layered sulfate" unit, which is further upslope from GT. This unit may represent a transition, or the onset of the transition, from a relatively "warm and wet" Mars to drier conditions [8,9]. As of Dec 2020 (sol ~2950), *Curiosity* has traversed through most of GT (Fig 1), from the phyllosilicate-rich Jura member at the bottom level of GT, Knockfarril Hill (KfH) member in middle elevations, and the "Fractured Intermediate Unit" (FIU) that sits below the Greenheugh Pediment unconformity (GPu) sandstone cap rock, which is part of the Siccar Point group [10]. Analyses of drill samples have shown that some GT samples contain siderite, KfH is the most clay-rich member observed within Gale to date, and a mineralogical change occurred below the GPu such that this strata is cristobalite- rather than clay-rich, similar to Telegraph Peak drill hole in Pahrump Hills (sol ~700) [11].

At least 4 chemical rock types have been observed in GT by ChemCam. [12] discusses the bedrock chemistry types: a ~54 wt% SiO_2 and 6–10 wt% MgO "coherent" endmember, and a ~56 wt% SiO_2 and 4–6 wt% MgO "rubbly" endmember. FIU is chemically similar to the rubbly endmember, but with lower K_2O. The strata just below the GPu is chemically similar to Pahrump Hills, with 5 wt% CaO, 11 wt% Al_2O_3, and 48 wt% SiO_2 [12].

Methods: We used data from a combination of *Curiosity* instruments: ChemCam spectra, ChemCam remote micro images (RMIs), Mastcam, and Mars Hand Lens Imager (MAHLI) images, to determine basic statistics about diagenetic features in Gale Crater. If a vein or concretion was visible in the RMI, but was not hit directly by the laser, we categorized that target as having a "diagenetic feature." ChemCam laser observation points that did not directly hit concretions were categorized as "concretion-rich bedrock" so as to differentiate between these bedrock compositions and allow for comparison with potentially unaltered, non-concretion bedrock. Those which did hit concretions directly were categorized as "concretion points." Observation points that hit a fracture fill were categorized as "vein" or "vein-like material." The 4 subsets of vein or vein-like material are Ca-sulfate; Mn/Fe-rich; F-bearing; and dark-toned strata. If we observed elevated CaO and S in an observation point, but did not hit a visible vein, we categorized the observation point as "Ca-sulfate cement." Cements typically coincide with light-toned material that is visible in MAHLI images. Since we use RMI images for this analysis, it is not a truly random sample of diagenetic features in GT.

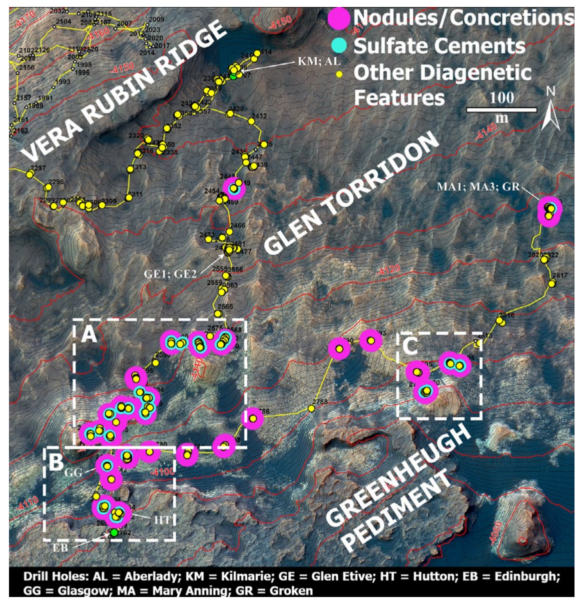

Fig 1: Glen Torridon map with locations of diagenetic features.

Results: Figure 1 shows the GT traverse and the locations where *Curiosity* observed potential concretions (pink) and sulfate cements (cyan). In GT, 62% of the ChemCam targets had a type of diagenetic feature. Of the total, 24% of the targets have concretions, and 10% have sulfate cements. Diagenetic features are frequently observed in the upper elevations of GT. At the buttes (Fig 1A), 80% of targets have diagenetic features, evenly split between cements and nodular features. Near the GPu (Fig 1B & C), 54% of targets have diagenetic features, and 40% have concretions and 11% have cements.

Figure 2 shows ternary diagrams of the major element oxides (moles) of the observed features compared to the coherent bedrock (large circle). Dark colors represent more MnO (wt.%) is present. Ca-sulfate veins rarely contain other soluble trace elements in high abundance (e.g., B and Li). Only 5% of targets contain detectable (>100 ppm) B, which is similar to the frequency observed in Sutton Island Murray [6]. Figure 2A shows a mixing line between concretion-rich bedrock compositions (♦) and the pure veins (+). Dark-toned concretions (★) are either Fe (up to ~45 wt% FeO_T) or Mg-rich (up to 15 wt% MgO), but lacking in MnO (Fig 2A). Just below GPu, vein-like materials that were Fe and Mn-rich (▼) were observed in close association with F-bearing materials (with ~2 wt% F) (■) [13]. In contrast, the Mary Anning and Groken drill location (Fig 2B) has Mn-rich dark-toned, potentially concretions (★), surrounded by bedrock elevated in Mn (♦) [14]. The concretions tend to be associated with Ca sulfate, contain elevated P, and form positive trends with FeO (up to 20 wt% FeO_T) and MgO (up to 15 wt% MgO) [14]. At the same location, Fe-rich dark-toned strata targets (▲) are observed with up to 30 wt% FeO_T (Fig 2B).

Discussion: We observe diagenetic features throughout GT, and cements and concretions tend to be more abundant near the GPu. The proximity of the capping GP unit suggests a relationship between the diagenetic features—veins and vein-like materials and concretions—and the alteration of the bedrock beneath the GPu. Chemical trends of the major elements of the Fe- and Mg-rich concretions are extended by the F-bearing materials, suggesting these two groups are related to the same set of diagenetic events. The presence of Ca-sulfate-cemented bedrock and other Ca-sulfate features at upper elevations of GT is suggestive of a potential transition into the sulfate unit. However, this is overprinted by the likely alteration of the bedrock beneath the GPu. More evidence, i.e., continued observation and increased frequency of sulfate features up to the sulfate unit, is needed to make conclusions about the sulfate features in GT.

Very localized Mn-rich bedrock and dark-toned features (potential concretions) occur at Harlaw Rise (sol ~2450) and at the Mary Anning and Groken drill locations within KfH. The Mn-enrichment of the bedrock suggests that this bedrock is Mn-cemented. We have observed Mn enrichments within the bedrock in other locations in GT (e.g., in the Jura), though not as abundantly as those found at the Groken drill location or in Hutton veins, suggestive of widespread Mn-rich fluids in GT. The dark-toned strata form a different trend on Fig 2B, suggesting at least one other diagenetic fluid flowed through these materials. The major elements of the dark-toned strata have similar composition to the concretions seen in GT, suggesting a relationship there.

Implications for timing. Likely multiple early- and late-stage fluid events with substantially different chemistries occurred in GT (e.g., those bearing sulfates, Mn, Fe, F, carbonate, silica, etc). Specifically, early fluids likely brought in sulfates and Mn to cement bedrock in different events. In one formation scenario, Mn cemented bedrock could have been reworked by later fluids to form concretions near Mary Anning and Groken. Concretions and vein-like materials occur just below the GPu, suggesting GP may have been present during the formation of these features during a late-stage fluid event. Ca-sulfate veins appear to cross-cut all features; likely these were the last set of fluid events that occurred in GT. We hypothesize a long history of groundwater alteration with multiple fluid events to account for changes in water chemistry.

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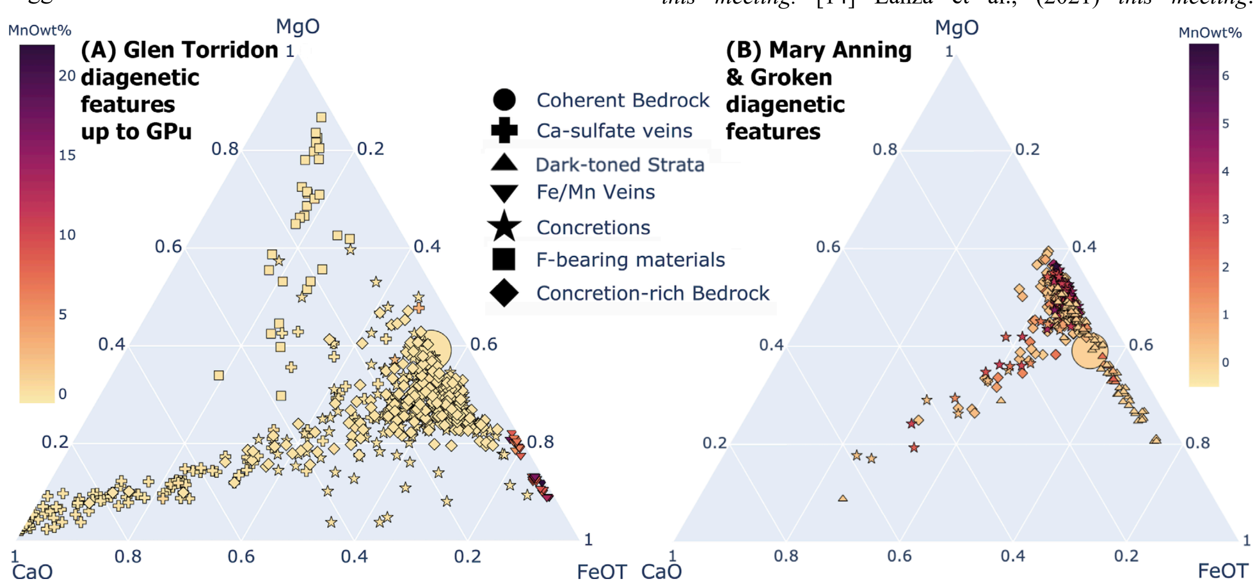

Fig 2: A) Major element oxide chemistry (moles) of the diagenetic features for the traverse from sol 2300 to the base of GPu, where colors represent wt.% MnO. B) Major element chemistry of the diagenetic features at the Mary Anning and Groken drill location.